InGaP/InGaAs-on-Ge Concentrator Solar Cell for Space Power Generation

Contract—

NAS3-99174

Author—

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Contractor—

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WORK PERFORMED DURING THIS PERIOD

Task 1: Growth and characterization of a lattice-matched passivating window for InGaP

$Al_{0.33}In_{0.67}P$ has been chosen as the lattice-matched passivating front and back window layer of the 1.62–eV InGaP top cell. As described in the previous report, secondary electron mass spectrometry (SIMS) analysis of the films revealed that the oxygen concentration in these films was in the low to mid-$10^{17}/cm^3$ level. In order to reduce the oxygen content in the AlInP window layer, we are planning to replace our precursor for aluminum (TMAl) with an ultra-pure, very low oxygen containing TMAl source. This should be accomplished within the next month.

Task 4. Fabrication and testing of two-terminal InGaP/InGaAs monolithic tandem cells on GaAs substrates.

Figure 1 shows a schematic diagram of the current design of our dual-junction cell. The 1.1–eV bottom cell is comprised of a 0.5–μm n+ $In_{0.2}Ga_{0.8}As$ emitter, a 3.0-μm p $In_{0.2}Ga_{0.8}As$ base and a 0.05–μm $In_{0.68}Ga_{0.32}P$ window layer. The 1.62–eV top cell in the initial design[5] consisted of a 0.05–μm n+ $In_{0.68}Ga_{0.32}P$ emitter, a 1.5–μm p $In_{0.68}Ga_{0.32}P$ base, a 0.05–μm p+ $In_{0.68}Ga_{0.32}P$ back surface field, and a 0.05–μm n $Al_{0.33}In_{0.67}P$ window layer. We have thinned the top cell in the current design as described below. A p++/n++ $In_{0.2}Ga_{0.8}As$ tunnel junction test structure, with the same thickness (0.05 μm) and doping levels (1x 10^{19} /cm^3) used in the dual-junction cell was evaluated prior to its incorporation in the dual-junction cell. We have chosen to use InGaAs as the tunnel junction interconnect compound since it is easily degenerately doped. All of the dual-junction cell structures were grown on GaAs substrates. Time constraints prevented us from completing the development of the GaAs-on-Ge growth process. As a result, no cell structures were grown on GaAs-coated Ge.

Doping	Layer	Thickness	Section
	Contact		
n++	$In_{0.2}Ga_{0.8}As$	0.1 µm	
n	$Al_{0.33}In_{0.67}P$	0.04 µm	1.62 eV Top Cell
n+	$In_{0.68}Ga_{0.32}P$	0.05 µm	1.62 eV Top Cell
p	$In_{0.68}Ga_{0.32}P$	0.3 µm	1.62 eV Top Cell
p+	$In_{0.68}Ga_{0.32}P$	0.05 µm	1.62 eV Top Cell
p	$Al_{0.33}In_{0.67}P$	0.05 µm	1.62 eV Top Cell
p++	$In_{0.2}Ga_{0.8}As$	0.02 µm	Tunnel Junction
n++	$In_{0.2}Ga_{0.8}As$	0.02 µm	Tunnel Junction
n+	$In_{0.68}Ga_{0.32}P$	0.05 µm	1.1 eV Bottom Cell
n	$In_{0.2}Ga_{0.8}As$	0.5 µm	1.1 eV Bottom Cell
p	$In_{0.2}Ga_{0.8}As$	3.0 µm	1.1 eV Bottom Cell
p	$In_{0.68}Ga_{0.32}P$	0.05 µm	1.1 eV Bottom Cell
	Buffer Scheme		
p	GaAs 6° off towards (111)B		
	Contact		

Figure 1. Epi-layer structure of the 1.62 eV InGaP/1.1 eV InGaAs dual-junction cell.

The first batch of 1.6–eV/1.1–eV dual-junction cells processed in our laboratory was bottom cell current limited.[5] This was believed to be one of the reasons for the low AM0, one–sun efficiency (12.9% without AR-coating, estimated to be 17% with an optimized anti-reflection coating) of those cells. Calculations have since shown that in order to obtain 100% quantum efficiency (QE) from the bottom cell, while maintaining a QE of at least 90% from the top cell, the top cell had to be thinned to 0.33 µm (compared to 1.65 µm in the first batch). Shown in Figure 2 is the light current-voltage (I-V) characteristic of a 1.62–eV/1.1–eV n/p dual-junction cell with a thinned top cell.[5] The cell is characterized by an open-circuit voltage (Voc) of 1.73 mV, a short-circuit current density (Jsc) of 19.14 mA, a fill factor (FF) of 78.5%, and an AM0, one-sun efficiency of 19.07%. The top cell in this case consisted of a 0.05–µm n+ $In_{0.68}Ga_{0.32}P$ emitter, a 0.3–µm p $In_{.68}Ga_{.32}P$ base, a 0.05–µm p+ $In_{.68}Ga_{.32}P$ back surface field, and a 0.04–µm n $Al_{.33}In_{.67}P$ window layer. The efficiency of this dual-junction cell, although higher than the first batch, is still significantly lower than the predicted value of 27%. The external quantum efficiency (EQE) of the subcells of the dual-junction cells was measured using appropriate filters, and the results are shown in Figure 3.

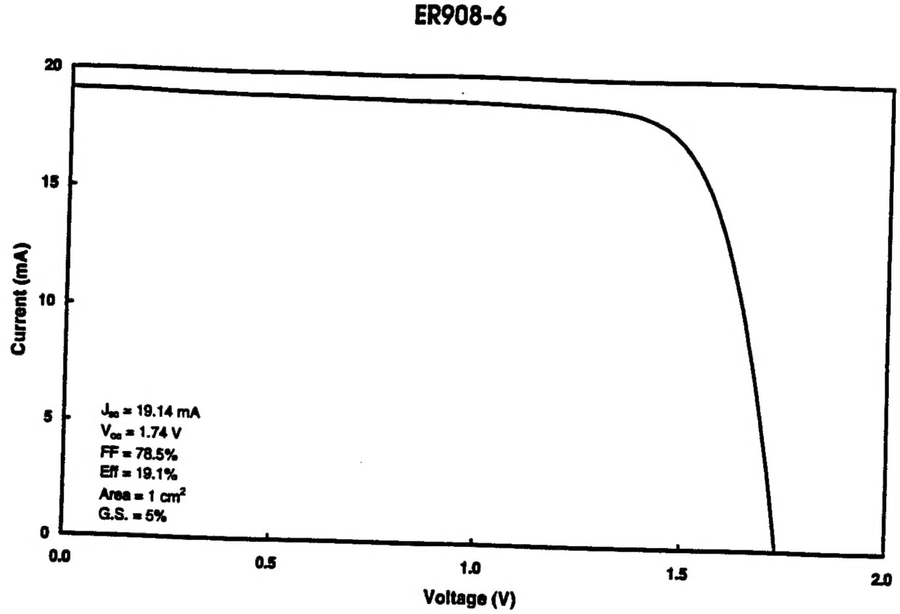

Figure 2.–I-V characteristics of an AR-coated 1–cm^2 1.62–eV n/p InGaP/1.1–eV InGaAs dual-junction cell.

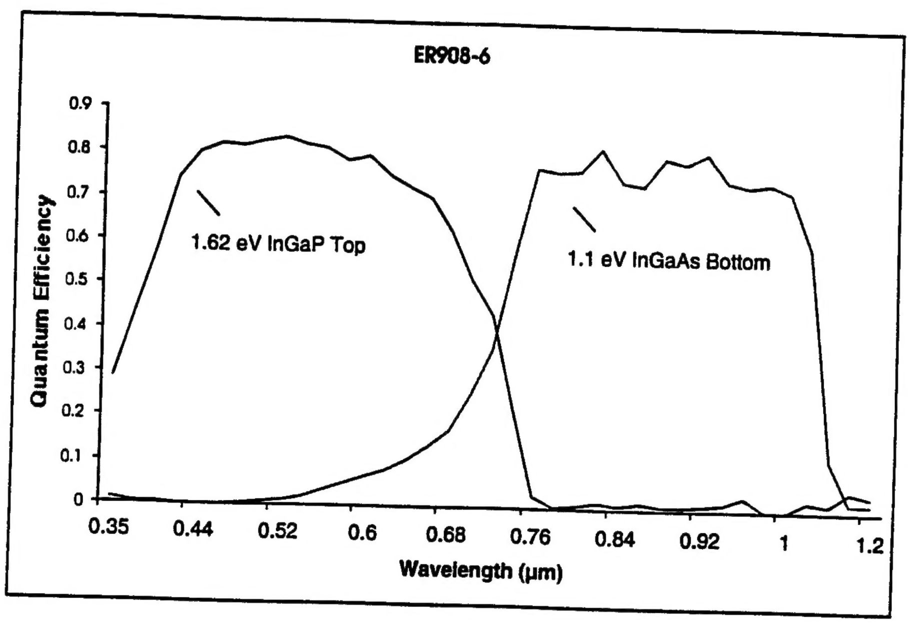

Figure 3.–External quantum efficiency of the subcells of a 1–cm^2 1.62–eV n/p InGaP/ 1.1–eV InGaAs dual-junction cell.

CURRENT PROBLEMS AND PROPOSED CORRECTIVE ACTIONS

Analysis of the I-V and EQE data and comparison with computer modeled data shows that the performance of the dual-junction cell is still being controlled by the bottom cell, in spite of the top cell thinning. This is evidenced by the fact that the measured AM0, Jsc of the dual-junction cell prior to AR-coating was 14.4 mA/cm^2, whereas the Jsc of the stand-alone InGaP cell under similar conditions was 15.9 mA/cm^2. If we further thin the top cell to achieve current matching conditions, then the Jsc of the dual-junction cell is expected to be the average of these two values, which is 15.2 mA/cm^2. The addition of an AR-coating will increase the value of the Jsc by a factor of 1.4, bringing it up to 21.2 mA/cm^2. Combining this Jsc with our experimental values of reverse saturation current density (J_0) of 1.7×10^{-33} A and a FF of 78.5%, we could obtain a Voc of 1.74 V, and an efficiency of 21.1%. Thus, optimization of top cell thinning alone will immediately improve the efficiency of the dual cell by 2 efficiency points.

Another factor limiting the performance of our dual-junction cell is the use of a 1.1–eV InGaAs tunnel junction, which absorbs some of the red light that the bottom cell is designed to convert. Calculations indicate that the use of a non-absorbing tunnel junction (such as 1.62–eV InGaP) would result in a 6% increase in the Jsc of the bottom cell. Since our dual-junction cell is bottom cell current-limited, this would increase the Jsc of the bottom cell to 15.3 mA/cm^2 without AR-coating. If we thin the top cell to achieve current matching conditions, then following the same argument as in the previous paragraph, Jsc of the dual-junction cell would increase to 15.6 mA/cm^2 without AR-coating, and to 21.8 mA/cm^2 with AR-coating. This will bring the efficiency up to 21.8%, using the same calculations as in the previous paragraph. SIMS analysis of our dual-junction cell structure has shown no evidence of dopant diffusion from the tunnel junction into the active layers.

Further improvement in the dual-junction cell efficiency is possible by thinning the front window. Modeling has shown that while the actual front window thickness is 400 Å, about half of the carriers generated therein are collected, so that the effective window thickness is only 200 Å. If we reduce the actual window thickness to 200 Å, we will have an effective window thickness of about 100 Å. This would result in an efficiency of 22.1% for the dual-junction cell. Significant improvements in the AlInP window layer quality is anticipated when the unacceptably high oxygen concentration (1.0×10^{17}/cm^2) in that layer is reduced. Calculations show that a perfect (no loss) window would result in a further improvement in efficiency from 22.1% to 24.3%.

WORK TO BE PERFORMED DURING THE NEXT PERIOD

During the next reporting period, the emphasis will be on large area pulse solar simulator (LAPPS) testing of the individual InGaP and InGaAs cells under 1 to 20 sun concentrations. These tests could not be done during the current reporting period, because the test facility at the Glenn research center is being rebuilt. The cell structures and processing parameters will continue to be optimized to realize the highest possible efficiency values under concentrator conditions. For the dual-junction cell, initial efforts during the next reporting period will be limited to optimizing the structure and processing to obtain the highest efficiency values under AM0, one-sun conditions, until the individual cell structures are optimized for higher concentrations.

COST AND COMPLETION ESTIMATES

The current costs have been calculated and the estimates are as follows:

- Total Costs (cumulative) through September 22, 2000........................ $ 82,406
- Estimated Costs for the following quarter.. $ 50,000
- Estimated Costs to the contract completion $213,427
- Estimated physical completion through September 22, 2000 .... 27%

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Analysis of the I-V and EQE data, and comparison with computer-modeled data, shows that the performance of the dual-junction cell is still being controlled by the bottom cell, in spite of top cell thinning. Further improvement in the dual-junction cell efficiency is possible by thinning the front window.

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